DIODE-PUMPED ALKALI AMPLIFIER

BY

William F. Krupke   (USA)

1564 Foothill Road

Pleasanton, CA 94588

5

DIODE-PUMPED ALKALI AMPLIFIER

10   This is a continuation-in-part of U.S. Patent Application Serial No.

10/000,508, titled "Diode-Pumped Alkali Laser" filed October 23, 2001 and

incorporated herein by reference.

BACKGROUND OF THE INVENTION

15 ### Field of the Invention

The present invention relates to laser amplifiers, and more specifically to

diode-pumped alkali amplifiers (DPAAs).

Description of Related Art

20   U.S. Patent Application Serial No. 10/000,508 describes a new class of

diode-pumped alkali lasers (DPALs). The DPAL device comprises 1) a laser gain

medium formed of an atomic alkali vapor, appropriate rare gas buffer gas or gasses,

and a selected small molecular weight gas; 2) an optically assessable container (cell,

capillary, vessel, etc.) containing the laser gain medium; 3) a laser resonator cavity,

containing the laser gain medium, one of which including cavity mirrors that allow

for the irradiation of the alkali vapor gain medium; and 4) a semiconductor laser

5   diode (or diode array) whose output radiation is used to optically excite alkali atoms

of the laser gain medium in the $^2S_{1/2}$ – $^2P_{3/2}$ resonance transition (so-called D_2 line).

The semiconductor laser pump irradiation induces a population inversion between

the $^2P_{1/2}$ and ground $^2S_{1/2}$ levels and laser oscillation on the $^2P_{1/2}$ - $^2S_{1/2}$ transition

(so-called D_1 line).

10   From the teachings of the parent application, the efficient conversion of

pump radiation can be realized, even utilizing a semiconductor laser diode pump

whose spectral width is many times the spectral width of the homogeneously-

broadened D_2 line as a result of proper laser design, taking into account substantial

power absorption and transfer through the Lorentizian wings of the D_2 line. The

15   principal DPAL performance characteristics, projected using a DPAL design,

calculations have been confirmed experimentally. This success achieved with alkali

laser oscillators prompted an examination of the feasibility and practicality of diode-

pumped alkali amplifiers, DPAAs.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide efficient, compact, high-power, near-diffraction-limited sources of radiation in the near infrared spectral region.

5   It is another object of the invention to provide a new class of power amplifiers that can be pumped by conventional high-power, multimode, relatively-broadband 1-D and 2-D laser diode arrays, wherein the pumped amplifier gain medium comprises an atomic vapor of one of the alkali elements (Li, Na, K, Rb, Cs), buffered with a mixture of rare-gas (He, Ar, Kr, Ne, or Xe) and selected molecular

10   gases.

These and other objects will be apparent to those skilled in the art based on the disclosure herein.

The use of an alkali atomic vapor element as laser active specie in a near infrared Diode-Pumped Alkali Laser (DPAL) has been disclosed in U.S. Patent

15   Application Serial No. 10/000,508, titled "Diode-Pumped Alkali Laser" filed October 23, 2001, and incorporated herein by reference. In the basic DPAL device, excitation to the n $^2P_{3/2}$ electronic level by a single diode laser pump source leads to a population inversion between the first excited electronic $^2P_{1/2}$ level and the ground $^2S_{1/2}$ level, permitting the construction of efficient, high-power, compact DPAL laser

20   oscillators in the near infrared spectral region.

The present invention provides efficient, compact, high-power, near-diffraction-limited sources of radiation in the near infrared spectral region. The

invention provides a new class of power amplifiers that can be pumped by conventional high-power, multimode, relatively-broadband 1-D and 2-D laser diode arrays, wherein the pumped amplifier gain medium comprises an atomic vapor of one of the alkali elements (Li, Na, K, Rb, Cs), buffered with a mixture of rare-gas

5   (He, Ar, Kr, Ne, or Xe) and selected molecular gases. Given the central role of the alkali atomic vapor as the entity providing amplifier gain, this new type of amplifier is herein designated as the diode-pumped alkali amplifier (DPAA).

The three lowest lying electronic levels of the alkali atom are utilized in the present DPAA designs. In the DPAA, the alkali atom is pumped at a wavelength

10   matching the wavelength of the $^2S_{1/2}$ – $^2P_{3/2}$ electric-dipole-allowed transition (the so-called D_2 transition). After kinetic relaxation of pump excitation energy to the $^2P_{1/2}$ electronic level, a population inversion density is created between the excited $^2P_{1/2}$ and the $^2S_{1/2}$ ground level, producing optical gain in the electric-dipole-allowed $^2P_{1/2}$ – $^2S_{1/2}$ transition (so-called D_1 transition).

15   In DPAA operation, pump radiation centered at the pump wavelength $\lambda(D_2)$ matching the D_2 transition is directed into an amplifier gain cell containing alkali atoms and buffer gases. The alkali atoms in the amplifier gain cell are selectively pumped into the $^2P_{3/2}$ electronic level via the D_2 transition, whereupon these atoms collisionally relax to the lower lying $^2P_{1/2}$ electronic level before they can

20   radiatively decay back to the $^2S_{1/2}$ ground level, due to the presence of the buffer gas(es). The buffer gas(es) also serve to collisionally broaden the alkali atom D-transitions, rendering them homogeneously broadened.

The D_2 transition wavelengths for Cs, Rb, and K lie in the spectral region ~760-850 nm for which powerful and efficient laser diode arrays are commercially available. Therefore, these particular alkali atoms are utilized in preferred DPAA embodiments.

5   A basic DPAA device configuration takes the form of an "end-pumped" configuration, accommodating the fact that the DPAA produces optical gain using a "three-level" population inversion scheme. In this basic configuration, the alkali-buffer gas amplifier gain medium is contained within a cell, which is fitted with flat optical windows at each end. These window surfaces may be coated with multilayer

10   dielectric stacks to reduce reflection losses of pump and amplified radiation from these surfaces upon entering and/or exiting the amplifier gain cell. To energize the DPAA, pump radiation provided by a laser diode pump array having a wavelength centered at the wavelength $\lambda(D_2)$ matching the D_2 transition is directed into the amplifier gain cell generally parallel along the cell axis, through a first gain cell

15   window. Pump radiation propagates through the gain cell, progressively being absorbed by alkali atoms. The pump radiation may freely propagate in the cell volume and reflect periodically from the wall of the gain cell, depending on the DPAA design. Pump radiation may be substantially absorbed in a single pass of the gain cell, or after a second pass through the gain cell, effected by placing a suitable

20   mirror at the end of the gain cell. The absorbed pump radiation produces optical gain at a wavelength $\lambda(D_1)$ centered at the wavelength of the D_1 transition.

To obtain amplification and extract power from the DPAA, a low power, near diffraction-limited source of radiation (often called a master oscillator, or MO) with a wavelength $\lambda(D_1)$ centered at the wavelength of the D_1 transition of the alkali vapor contained in the amplifier gain cell, is directed into the amplifier gain cell,

5 generally along the axis of the gain cell, and spatially overlapping a substantial fraction of the volume of the alkali-buffer-gas medium excited by the pump radiation. As the low power MO passes through the amplifier cell it initially grows exponentially in intensity until it becomes sufficiently intense to saturate the gain of the alkali gain medium and extract a substantial portion of the pump excitation

10 deposited in the amplifier.

In one embodiment, the pump and MO beams are spatially overlapped and generally co-aligned in direction of propagation, and directed into the amplifier gain cell. In this basic configuration, the MO beam passes once through the gain cell and exits from the opposite end. In an alternative preferred embodiment, and

15 taking advantage of the fact that the optical gain in the alkali-buffer-gas medium is polarization insensitive (even if excited by a polarized pump beam), polarized MO and pump beams are utilized and an optical arrangement is employed that allows the amplifier MO beam to pass twice through the amplifier gain cell so as to increase the efficiency of extraction of power from the DPAA.

20 In another embodiment that avoids the need to utilize dichroic optical elements, the radiation from a laser diode pump array is coupled into the amplifier gain cell using a hollow lens-duct. A polarized MO beam is coupled into the gain

cell along the co-aligned axes of the hollow lens-duct and the amplifier gain cell; this input MO beam is doubled passed through the amplifier gain cell, and extracted from the DPAA using a Faraday rotator and output polarizer plate.

Many other DPAA embodiments will be obvious to those skilled in the art

5   based of the teaching herein. Unexpectedly high power conversion efficiency of relatively broadband diode pump array radiation into amplified beam power can be realized in a DPAA because it proves possible to effectively deposit much of the pump power into the alkali atoms through the homogeneously-broadened Lorentzian wings of the pump transition.

10

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic layout of a master-oscillator, power amplifier (MOPA) implemented with a diode-pumped alkali amplifier (DPAA).

Figure 2 shows a first embodiment of a double-passed, diode-pumped

15   alkali power amplifier in a master-oscillator, power amplifier (MOPA) laser system.

Figure 3 shows a second embodiment of a double-passed, diode-pumped alkali power amplifier in a master-oscillator, power amplifier (MOPA) laser system.

Figure 4 shows the optical-to-optical power conversion efficiency of a rubidium amplifier as a function of n_o*l_s (assuming a 20 kW/cm^2 pump flux and a

20   20 W/cm^2 input flux).

Figure 5 shows the output power flux of a rubidium amplifier as a function of n_o*l_s (assuming a 20 kW/cm^2 pump flux and a 20 W/cm^2 input flux).

Figure 6 shows the power gain of a rubidium amplifier as a function of

$n_o{}^*l_s$ (assuming a 20 kW/cm^2 pump flux and a 20 W/cm^2 input flux).

Figure 7 shows the population density line integral of a rubidium

amplifier as a function of $n_o{}^*l_s$ (assuming a 20 kW/cm^2 pump flux and a 20 W/cm^2

5   input flux).

DETAILED DESCRIPTION OF THE INVENTION

Using the same steady-state, plane-wave, rate-equation approach adopted

to assess DPALs in the parent case, it was possible to calculate amplifier

10   performance of DPAAs. Systematic calculations of the performance of DPAA

devices were carried out in terms of the key pump drive and device parameters

(alkali number density, buffer gas mixtures and pressures, pump spectral intensity,

device geometry, etc.). From these calculations, it became clear that practical DPAA

designs could be realized, as a result of efficient "wing-pumping" of the

15   homogeneously-broadened D$_2$ line, enabling efficient narrowband power extraction

from the alkali amplifier in the spectrally-homogeneously broadened D$_1$ line. As is

well known, the availability of an efficient power amplifier at a given wavelength

permits the realization of a master-oscillator, power-amplifier (MOPA) laser system

configuration. Compared with the conventional laser oscillator (using the same gain

20   medium), the MOPA has the distinct advantageous property of achieving a near-

diffraction-limited, high power output beam from the MOPA by using a low-power

master-oscillator input beam having near-diffraction-limited beam quality, which is

relatively easy to provide. Additionally, since there are no wavelength selective

elements in the DPAA MOPA, other than the homogeneously-broadened D_1 gain

transition, spectrally narrowband power can be extracted from the DPAA when a

spectrally narrowband MO is employed in the MOPA. For this these advantages to

5   be practical, it is desirable that power amplifier gains >20-50 (per stage) be

achievable and that pump power delivered into the amplifier can be extracted with

high efficiency. DPAAs, as a class, possess these characteristics.

To illustrate this assertion, the results of DPAA performance calculations

are presented here for the specific case of a rubidium alkali amplifier. Figure 1

10   shows a schematic of a master-oscillator, power amplifier (MOPA) implemented

with a diode-pumped alkali amplifier (DPAA). This basic DPAA architecture

comprises a diode pump source 10 (either single broad stripe, or multi-stripe bar, or

2-D multi-stripe bar array) emitting a beam 12 at a wavelength $\lambda(D_2)$ matched to the

wavelength of the corresponding D_2 transition of the alkali vapor gain medium 14

15   contained within the alkali amplifier cell 16. The amplifier gain medium comprises

the working alkali vapor and one or more buffer gases whose combined purposes

are to sufficiently broaden the D_2 and D_1 alkali atom transitions, and to thermalize

the populations between the two excited ^2P levels in a time shorter than the radiative

lifetimes of the ^2P levels. The pump beam is directed into the alkali power amplifier

20   cell generally along the cell axis (and may be double-passed through the amplifier

cell by reflecting the pump beam back through the amplifier cell from a mirror (e.g.,

mirror 22) placed at the end of the amplifier cell, a mirror that is preferentially

reflective at the wavelength of the pump beam). A relatively weak (compared to the

pump beam intensity) input beam of radiation 18 (from the master oscillator 20) at

wavelength $\lambda(D_1)$ matching the wavelength of the D_1 transition of the alkali gain

medium is also directed into the alkali power amplifier gain cell, generally along the

5   cell axis, co-parallel to the pump beam. The intensity of this input beam at

wavelength $\lambda(D_1)$ is amplified when passing through the pump excited alkali gain

medium, as a result of the population inversion created between the $^2P_{1/2}$ level and

the ground $^2S_0$ level produced by absorption of pump radiation at wavelength $\lambda(D_2)$.

As in the DPALs oscillator implementation, the half-power spectral width

10   of the pump diode can be many times the half-width of the (Lorentizian)

collisionally-broadened width of the alkali vapor medium, since it is feasible to

efficiently absorb pump radiation by the alkali atoms in the far spectral wings of the

D_2 pump transition. Although the present invention is operable using pump diodes

that have narrow spectral widths, e.g., much less than 1 nm, the advantage provided

15   by the present invention lies in the fact that it is operable using commercially

available laser diode, which currently generally have spectral widths within a range

from about 1 nm to 6 nm. Since the alkali vapor medium is homogeneously

broadened by collisions with the buffer gas(es), absorbed pump energy is available

to be transferred efficiently to the relatively weak input beam. The relatively weak

20   input beam can be extracted from the amplifier after passing once through the

power amplifier cell, or it too may be double-passed through the power amplifier

gain cell, further increasing the power in its beam. Using appropriate optical

elements, the pump and input beams can be combined at the entrance to the

amplifier gain cell, and also separated from each other after double passing through

the gain cell. There are several obvious combinations of input and reflector optical

elements that can be employed to perform the pump and input beam combining

5   before the gain cell, and beam separation after amplification (either single pass or

double pass). Two such embodiments are shown in Figures 2 and 3.

Figure 2 shows an embodiment of a double-passed, diode-pumped alkali

power amplifier in a master-oscillator, power amplifier (MOPA) laser system. The

master oscillator (MO) may be a diode-pumped alkali laser (DPAL) or may be any

10   other low-power master oscillator laser emitting at wavelength $\lambda(D_1)$. The pump

beam 30 (from diode pump laser 32) at wavelength $\lambda(D_2)$ and the low power input

beam 34 (from the master oscillator 36) at wavelength $\lambda(D_1)$ are both linearly

polarized. The MO input beam is passed through an input-output polarizing beam

splitter 38 and a Faraday Rotator (FR) cell 40. The FR cell rotates the input beam

15   polarization by 45 degrees rendering the polarization perpendicular to the plane of

the page, as indicated by dots along the beam path). This MO beam next passes

through a dichroic thin-film polarizer 42 that is oriented to provide high

transmission at wavelength $\lambda(D_1)$. The pump beam is directed toward the dichroic

thin-film polarizer and its plane of polarization is oriented (here parallel to the plane

20   of the page) is such a way that it is highly reflected at wavelength $\lambda(D_2)$. With this

arrangement, the MO and pump beams are spatially overlapped at the thin film

polarizer and generally co-directed toward and into the alkali power amplifier 44.

The pump and MO beams are each propagated through the alkali gain cell and are

redirected for a second pass through the cell by a mirror 46,placed at the end of the

cell. The mirror is coated so as to provide high reflectivities at wavelengths $\lambda(D_1)$

and $\lambda(D_2)$. Generally, the multimode pump beam will be substantially more

5   divergent than the MO beam, and the pump radiation may be propagated generally

through the cell by reflecting periodically from the cell wall surfaces. Generally, the

beam quality of the MO will be near-diffraction-limited and will be propagated

through the cell without reflection from the cell wall surfaces. During its double pass

through the power amplifier cell containing a mixture of alkali vapor and buffer

10   gases, the pump beam is highly absorbed at the wavelength $\lambda(D_2)$ of the $^2S_{1/2}$ - $^2P_{3/2}$

transition (so-called D_2 transition) of the subject alkali vapor. This pump excitation

process leads to a population inversion and gain on the $^2P_{1/2}$ - $^2S_{1/2}$ transition (so-

called D_1 transition) at the wavelength $\lambda(D_1)$. The relatively weak input beam from

the master oscillator is greatly amplified in power upon passing through the gain

15   cell. The amplified MO beam retains its polarization and exits the amplifier cell,

passing through the dichroic thin-film polarizer and the Faraday Rotator cell a

second time, undergoing an additional 45-degree rotation. The polarization of the

amplified beam at wavelength $\lambda(D_1)$ is now oriented to reflect with high efficiency

from the input/output polarizing beam splitter.

20   Figure 3 shows another embodiment of a double-passed, diode-pumped

alkali power amplifier in a master-oscillator, power amplifier (MOPA) laser system.

The master oscillator (MO) may be a diode-pumped alkali laser (DPAL) or may be

any other low-power master oscillator laser emitting at wavelength $\lambda(D_1)$. This embodiment has the advantage of dispensing with the dichroic thin-film polarizer component needed in the implementation of the embodiment shown in Figure 2 and described above. The radiation 50 at wavelength $\lambda(D_2)$ from a diode pump array 52

5   is radiance conditioned and is directed into the alkali power amplifier gain cell 54 through a hollow lens duct concentrator 56. The pump radiation propagates down the length of the gain cell, reflecting off of the cell sidewalls 58 that are coated to highly reflect radiation at the pump wavelength. A mirror 60 is placed at the far end of the amplifier gain cell to reflect pump radiation that has not yet been absorbed by

10   the alkali vapor back through the cell for a second pass. In this embodiment, the relatively weak master oscillator input beam 62 at wavelength $\lambda(D_1)$ that is to be amplified is linearly polarized and directed through a plate polarizer 64 so as to transmit the input beam and send it toward the alkali gain cell, first passing through a Faraday Rotator cell 66 (which rotates the polarization of the input beam by 45

15   degrees) and then passing through a hole in the radiance conditioned pump array. The input beam is strongly amplified in power upon double passing through the alkali power amplifier, preserving its high spatial beam quality and narrow spectral width, due to the gain produced at wavelength $\lambda(D_1)$ when the pump radiation at wavelength $\lambda(D_2)$ is absorbed by the subject alkali vapor in the gain cell. After its

20   second pass through the gain cell, the strongly amplified beam at wavelength $\lambda(D_1)$ is directed through the Faraday Rotator cell a second time, whereupon its polarization is rotated a further 45 degrees. Upon exiting the Faraday Rotator cell,

the beam's polarization is now oriented so that it will be highly reflected from the

plate polarizer. In this manner the amplified beam 62' at wavelength $\lambda(D_1)$ is

extracted from the MOPA system.

Figure 4-7 show the calculated performance of a doubled-passed (pump

5   and input beams) rubidium DPAA under adoption of the parameter assumptions

listed in Table 1. Each of these figures plots a performance parameter versus the

quantity $(n_0 l_s)$ that appears integrally in the rate equations describing both DPALS

and DPAAs. Here, n_0 denotes the total alkali atom number density in the gain

medium, and l_s denotes the length of the alkali gain column (here also assumed to be

10   the length of the amplifier gain cell).

Table 1. Assumed Parameters of a Rubidium Diode-Pumped Alkali

Amplifier (DPAA).

Parameter	Value
pump flux	20 kW/cm²
pump spectral width (FWHM)	2 nm
Input flux	20 W/cm²
helium pressure	10 atm

15   In Figs. 4-6 the optical-to-optical power conversion efficiency, output

power flux, and power gain all evidence a similar behavior as a function of the

quantity, $(n_0 l_s)$. Figure 7 shows that the population density line integral, N2 is

precisely linearly proportional to the value of $(n_0 l_s)$. If a Rubidium amplifier that is

90% optically efficient is desired, for the assumed pump flux of 20 kW/cm² and an

20   input flux of 20 W/cm², then, from Fig. 4, $(n_0 l_s)$ must have the value 2.25 x 10^{14}

atom/cm^2. If we assume that the rubidium alkali number density is 2.25 x 10^{13}

atoms/cm^3, then the gain (amplifier cell) length, l$_s$ must be 10 cm. These device

parameter values are quite reasonable, and it is anticipated that practical (efficient

and compact) rubidium diode-pumped amplifiers can be realized. It is anticipated

5   that similar amplifier performance levels can be achieved using the other alkali

atoms.

The foregoing description of the invention has been presented for

purposes of illustration and description and is not intended to be exhaustive or to

limit the invention to the precise form disclosed. Many modifications and variations

10   are possible in light of the above teaching. The embodiments were chosen and

described to best explain the principles of the invention and its practical application

to thereby enable others skilled in the art to best use the invention in various

embodiments and with various modifications suited to the particular use

contemplated. The scope of the invention is to be defined by the following claims.